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A Reexamination of the Crop Water Stress Index

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Summary. Hand-held infrared radiometers, developed during the past decade, have extended the measurement of plant canopy temperatures from individual leaves to entire plant canopies. Canopy temperatures are determined by the water status of the plants and by ambient meteorological conditions. The crop water stress index (CWSI) combines these factors and yields a measure of plant water stress. Two forms of the index have been proposed, an empirical approach as reported by Idso et al. (1981), and a theoretical approach reported by Jackson et al. (1981). Because it is simple and requires only three variables to be measured, the empirical approach has received much attention in the literature. It has, however received some criticism concerning its inability to account for temperature changes due to radiation and windspeed. The theoretical method is more complicated in that it requires these two additional variables to be measured, and the evaluation of an aerodynamic resistance, but it will account for differences in radiation and windspeed. This report reexamines the theoretical approach and proposes a method for estimating an aerodynamic resistance applicable to a plant canopy. A brief history of plant temperature measurements is given and the theoretical basis for the CWSI reviewed.

The use of canopy temperatures to detect water stress in plants is based upon the assumption that, as water becomes limiting, transpiration is reduced and the plant temperature increases. Plant temperatures have been measured by various means for at least a century and a half. Early work largely ignored meteorological factors and concentrated, by necessity of limited equipment, to measuring the temperature of individual leaves. During the early part of this century, a controversy raged concerning the possibility that plant temperatures could be cooler than the surrounding air. With the development of infrared radiometers, the temperature of groups of leaves could be measured, the controversy concerning plant temperatures in relation to the air resolved, and the possibility of using plant temperatures to quantify plant water stress contemplated (Tanner 1963).

Within the past decade, small, portable infrared thermometers have become ubiquitous tools for the measurement of soil and plant temperatures. Infrared thermometry offered the possibility of rapid, quantitative, field measurements of plant water stress. Idso et al. (1981) presented an empirical method for quantifying stress by determining "non-water-stressed baselines" for crops. These baselines represent the lower limit of temperature that a particular crop canopy would attain if the plants were transpiring at their potential rate. In addition, estimation of the upper limit of temperature that a non-transpiring crop would attain was necessary, but the proposed method for extracting this limit was not straightforward. A crop water stress index (CWSI) was calculated by ratioing the difference between the measured canopy temperature and the lower limit to the difference between the upper and lower limits, at a particular vapor pressure deficit. This empirical approach has received considerable attention because of its simplicity and the fact that one needs only to measure canopy temperature, air temperature, and the vapor pressure deficit of the air. In the years since the index was proposed, some shortcomings have become evident. A criticism has been that the method does not account for net radiation and windspeed, and that the estimation of the upper limit is somewhat ambiguous. It has been observed that non-water-stressed baselines determined during cool periods were different than those obtained in warm periods (Bucks et al. 1985).

Shortly after the empirical approach of Idso et al. (1981) was reported, Jackson et al. (1981) presented a theoretical method for calculating the CWSI. The theory required an estimate of net radiation and an aerodynamic resistance factor, in addition to the temperature and vapor pressure terms required by the empirical method. Although the theoretical approach specified how the upper and lower limits can be evaluated, the additional measurements of net radiation and aerodynamic resistance, and perhaps some equations that appear more complex than they are, have resulted in this method not receiving the thorough field tests that the empirical method has undergone.

Thus, a reexamination of the theoretical approach is in order. This report consists of a brief history of plant temperature measurements, a review of the theoretical basis for the crop water stress index, and a discussion of some additional insights into the application of the theoretical approach for measuring crop water stress.

Historical Perspectives

Nearly a century and a half ago, Rameaux (1843) as cited by Ehlers (1915), placed a number of leaves on top of one another and wrapped the stack around a mercury thermometer. This experiment, crude by today's standards, may have been the beginning of research concerning plant temperatures in relation to their environment. The literature on this topic is rather sparse until the 1920's. By this time thermocouples had become standard equipment, making detailed leaf temperature measurements possible. Miller and Saunders (1923) used thermocouples to measure the temperature of leaves of crop plants in Kansas under natural conditions. Their results showed that turgid leaves of most crops were essentially at air temperature, but alfalfa was consistently below air temperature by about 1 °C. This was one of the first reports of leaf temperatures being less than air temperture. Further evidence of this effect was reported by Eaton and Belden (1929), who measured cotton leaf temperatures to be 2°

to 4° C less than air temperature in the hot, dry climate of Arizona. Later, Wallace and Clum (1938) reported leaf temperatures as much as 7 °C less than air. However, these results were not universally accepted. Curtis (1936, 1938) argued that transpirational cooling could not explain the results, but that erroneous air temperature measurements, radiative cooling, and other factors were the cause. Curtis's arguments were strong, and the view that leaves were always warmer than air prevailed for several decades, in spite of a number of reports to the contrary.

The work of Ehrler (1973) conclusively demonstrated that leaf temperatures could be cooler than the air temperature, and, in fact, were a function of the vapor pressure deficit of the air. In field experiments with cotton, he placed fine wire thermocouples in leaves and measured the air temperature and the vapor pressure at 1 m above the crop. His results showed a leaf-air temperature difference that ranged from −3° to +2° C, depending on the amount of soil water depletion. Plots of leaf-air temperature versus vapor pressure deficit were linear. Using infrared thermometers to measure canopy temperature (in contrast to the single leaf thermocouple measurements), Idso et al. (1981), and Jackson et al. (1981) exploited the relation between the plant-air temperature difference and the vapor pressure deficit to develop the CWSI, the subject of this paper. A review of canopy temperature and crop water stress research was reported by Jackson (1982), and recently by Idso et al. (1986).

Review of Theoretical Approach

The theoretical development of the crop water stress index is based on the energy balance at a surface, i.e.,

$$R_n = G + H + \lambda E\,, \tag{1}$$

where R_n is the net radiation (W m^{-2}), G is the heat flux into the surface (W m^{-2}), H the sensible heat flux (W m^{-2}) into the air above the surface, and λE is the latent heat flux (W m^{-2}).

The terms H and λE in Eq. (1) can be expressed as,

$$H = \varrho\, C_p (T_c - T_a)/r_a\,, \tag{2}$$

and,

$$\lambda E = \varrho\, C_p (e_c^* - e_a)/[\gamma (r_a + r_c)]\,, \tag{3}$$

where ϱ is the density of air (kg m^{-3}), C_p the heat capacity of air (J kg^{-1} °C^{-1}), T_c the canopy temperature (°C), T_a the air temperature (°C), e_c^* the saturated vapor pressure of the air (Pa) at T_c, e_a the vapor pressure of the air (Pa), γ the psychrometric constant (Pa °C^{-1}), r_a the aerodynamic resistance (s m^{-1}), and r_c the canopy resistance to water loss (s m^{-1}).

In practice, infrared thermometers are the instruments of choice to measure canopy temperatures for use in evaluating the crop water stress index. The instruments are generally hand-held and positioned such that their field of view encompasses mostly plant material, with little or no soil viewed. Thus, the radiation received by the radiometers is largely from vegetation, and the resulting temperature can be assumed to be the canopy temperature T_c.

Eqs. (2) and (3) are based on several assumptions. One is that the aerodynamic resistance (r_a) adequately represents the resistance to turbulent transport of heat (r_{ah}), water vapor (r_{av}), and momentum. This is not theoretically correct because transport processes of scalars (i.e., heat, water vapor, CO_2, etc.) differ from momentum transfer for vegetated surfaces (Thom 1972). Pressure drag augments the transfer of momentum relative to scalar quantities, therefore, r_a is less that either r_{ah} or r_{av}. Monteith (1973) has shown that, for full canopy cover, the difference between r_a and r_{ah} is relatively small and in most cases can be accounted for by correcting r_a with a constant (Brutsaert 1982).

A second assumption is that the source of latent and sensible heat is primarily from the vegetation. That is the underlying surface (i.e., soil) does not contribute significantly to H and λE values measured above the canopy. Both assumptions, although theoretically not valid, will cause only small errors for full canopy, non-stressed conditions, because most of the incoming radiation is absorbed, reflected or emitted by the vegetation. The errors can be reduced somewhat by considering that G is about 0.1 R_n for full canopies (Clothier et al. 1986), and writing $R_n - G = 0.9\,R_n = I_c R_n$, Eq. (1) becomes, $I_c R_n = H + \lambda E$, where I_c is an interception coefficient. Combining this expression with Eqs. (2, 3) and defining Δ as the slope of the saturated vapor pressure-temperature relation, i.e., $\Delta = (e_c^* - e_a^*)/(T_c - T_a)$, in units of Pa °C^{-1}, we obtain

$$T_c - T_a = \frac{r_a I_c R_n}{\varrho C_p} \cdot \frac{\gamma(1 + r_c/r_a)}{\Delta + \gamma(1 + r_c/r_a)} - \frac{e_a^* - e_a}{\Delta + \gamma(1 + r_c/r_a)}, \tag{4}$$

which relates the difference between the canopy and the air temperatures to the vapor pressure deficit of the air ($e_a^* - e_a$), the net radiation, and the aerodynamic and crop resistances.

The upper limit of $T_c - T_a$ can be found by allowing the canopy resistance r_c to increase without bound. As $r_c \to \infty$, Eq. (4) reduces to

$$(T_c - T_a)_{ul} = r_a I_{cu} R_n / \varrho C_p, \tag{5}$$

the case of a non-transpiring crop.

The lower bound, found by setting $r_c = 0$ in Eq. (4), is

$$(T_c - T_a)_{ll} = \frac{r_a I_{cl} R_n}{\varrho C_p} \cdot \frac{\gamma}{\Delta + \gamma} - \frac{e_a^* - e_a}{\Delta + \gamma}, \tag{6}$$

the case for a wet canopy acting as a free water surface. It is assumed that the aerodynamic resistances in Eqs. (5) and (6) are identical, although this assumption is not strictly valid (Choudhury et al. 1986).

Theoretically, Eqs. (5) and (6) form the bounds for all canopy-air temperature differences. However, the temperature difference for most well watered crops will be greater than the lower limit because most crops exhibit some resistance to water flow, even when water is not limiting. For these crops, the lower limit should be modified by replacing γ in Eq. (6) with $\gamma^* = \gamma(1 + r_{cp}/r_a)$, where r_{cp} is the canopy resistance at potential transpiration.

A crop water stress index can be defined as

$$\mathrm{CWSI} = \frac{(T_c - T_a) - (T_c - T_a)_{ll}}{(T_c - T_a)_{ul} - (T_c - T_a)_{ll}} \tag{7}$$

where $(T_c - T_a)$ is the measured temperature difference.

The purpose of the upper and lower limits is to form bounds by which the measured temperature can be normalized. The upper limit $(T_c - T_a)_{ul}$ represents a fictitious temperature difference that would occur if the canopy were instantly desiccated. That is, all water was removed from the canopy without any change in architecture. The roughness elements would remain the same but the canopy would be warmer because the net radiation would be balanced by sensible heat loss instead of latent heat loss. The net radiation would be less for the desiccated condition because the reflected and emitted radiation would be greater than for the "green" condition. The increased outgoing radiation could decrease R_n by about 10%, making $I_{cu} \approx 0.8$ for the upper limit.

The lower limit $(T_c - T_a)_{ll}$ represents another fictitious temperature difference, that which would obtain if the crop was well watered, with no internal inhibitions to transpiration other than r_{cp}. Under these conditions, the canopy temperature would be at a minimum for the existing environmental conditions. Eqs. (5) and (6) offer a means to evaluate these limits, providing that R_n is known, and that an adequate representation for the aerodynamic resistance is used.

Substituting Eqs. (4), (5), and (6) in (7), shows that R_n and r_a appear in both the numerator and denominator. Thus, the net radiation and windspeed at the time of measurement affect the canopy-air temperature difference $(T_c - T_a)$. The upper and lower limits must be calculated for the same environmental conditions that existed at the time of measurement. This is a major difference between the empirical and the theoretical methods. The empirical method assumes that the upper and lower limits are constant.

The Aerodynamic Resistance

Under neutral conditions (surface temperature essentially equal to air temperature) r_a can be calculated using

$$r_a = \{\ln[(z-d)/z_0]/k\}^2/U\,, \tag{8}$$

where z is the reference height (m), d the displacement height (m), z_0 the roughness length (m), k the von Karman constant (0.4), and U the windspeed (m s^{-1}). The terms z_0 and d can be represented as functions of the vegetation height (h). Monteith (1973) reported that $z_0 \approx 0.13\,h$, and $d \approx 0.63\,h$ for plant canopies with full cover.

In addition to being limited to neutral conditions, Eq. (8) becomes excessively large at low windspeeds. In fact as $U \to 0$, $r_a \to \infty$, and $(T_c - T_a)_{\mathrm{ul}} \to \infty$, an unrealistic result. Windspeeds <1 m s^{-1} frequently occur during the course of canopy temperature measurements, a fact that must be accounted for in the calculation of r_a. A further complication becomes evident at the lower windspeeds when the measurement of windspeed is considered. The stall speed of many anemometers is relatively large (i.e., 0.5 m s^{-1}), which means that a value of $U = 0$ can be recorded although the air may be moving above the canopy. Even without measurable horizontal wind, air movement takes place within the canopy because free convective conditions exist which results in buoyancy driven, energy containing eddies.

For non-neutral conditions, r_a is non-linear function of temperature. The defining equations, different for stable and unstable conditions, are solved by iteration. For a discussion of these relationships, see Garratt (1978), Brutsaert (1982), and Choudhury et al. (1986). In these expressions, the windspeed appears in the numerator as well as the denominator, somewhat moderating the increase in r_a with decreasing windspeed. However, these equations have not been validated for $U < 1\ \mathrm{m\ s^{-1}}$, leaving a question as to their applicability at low windspeeds.

Thom and Oliver (1977) included the influence of buoyancy on aerodynamic resistance in a semi-empirically based equation for r_a that reaches a finite limit as $U \to 0$. Their equation is

$$r_{ae} = 4.72\,\{\ln[(z-d)/z_0]\}^2/(1+0.54\,u)\,, \tag{9}$$

where r_{ae} represents an effective aerodynamic resistance. This equation overcomes several of the limitations of Eq. (8), and is much simpler to evaluate than the more theoretical equations for non-neutral conditions. It is obvious that a more critical evaluation of the aerodynamic resistance is needed to better understand its role in the determining the upper and lower limits of $T_c - T_a$.

Canopy Resistance at Potential Transpiration

The empirical approach requires the lower limit (the non-water-stressed baseline) to be experimentally determined for each crop of interest. The theoretical approach has a similar requirement.The canopy resistance experienced by the canopy under well-watered conditions must be evaluated. Experimentally, the determination of r_{cp} is much the same as for the non-water-stressed baselines. Canopy and air temperatures, vapor pressure deficit, net radiation and windspeed are measured for a well watered crop. Using these values in Eq. (6), with γ replaced by γ^*, will allow the calculation of r_{cp}. A number of measurements are required to adequately specify this value. O'Toole and Real (1986) estimated r_{cp} values from non-water-stressed baselines of Idso (1982), O'Toole and Hatfield (1983), and data for rice that they had measured. They reported r_{cp} values ranging from 13.5 for rice to 68.7 for a fig tree. Evaluation of r_{cp} from data reported in the literature is frequently hampered because T_a is usually not given.

The Temperature Dependence of Δ

The value of Δ in Eqs. (4) and (6) is dependent on temperature. It is the derivative with respect to temperature of the saturated vapor pressure-temperature relation. An exact mathematical description of this factor is rather complicated. However, it can be adequately approximated by

$$\Delta = 45.03 + 3.014\,T + 0.05345\,T^2 + 0.00224\,T^3\,, \tag{10}$$

where T is the average of the canopy and the air temperatures, $(T_c + T_a)/2$, expressed in °C.

The temperature dependence of Δ helps to explain the observation by Bucks et al. (1985) that both the slope and intercept of non-water-stressed baselines are larger when measured during warm periods than when measured during cool periods.

Examination of Eq. (6) shows that Δ appears in the denominator of both the slope and intercept terms, and R_n appears only in the intercept. The slope of the lower limit is $-1/(\Delta+\gamma)$. Thus, as the temperature increases, Δ increases and the slope increases (the absolute value of the slope decreases). Based only on temperature differences, the intercept decreases with increasing temperature. However, cool season R_n values are generally much less than those for warm seasons. Going from a cool to a warm period, the increase in the intercept due to higher R_n values offsets the decrease due to warmer temperatures. Thus warm season lower limits can be higher than those for cool seasons, as observed experimentally by Bucks et al. (1985).

Comparison with Experimental Data

The considerable number of reports containing canopy-air temperature difference data would suggest that ample data exists in the literature to adequately test the theoretical approach. Unfortunately, most reports lack a key parameter such as net radiation, windspeed, or air temperature. The lack of adequate data to test the theoretical approach is testimony to the appealing simplicity of the empirical approach.

Although an comprehensive test of the theory is not as yet available, a few reports suggest that adequate values can be predicted for the upper and lower limits. O'Toole and Hatfield (1983) measured the upper limit for corn, bean, sorghum, and cotton by cutting the root systems of three rows of plants, and measuring the resulting $T_c - T_a$. Calculations of $(T_c - T_a)_{ul}$ using Eqs. (5) and (9) yielded values well within the range of experimental values shown in their Fig. 3. Jackson (1982) reported a value of $(T_c - T_a)_{ul} \approx 5$ for a senesced wheat crop. Eqs. (5) and (9) predicted a value of 5.6 °C.

O'Toole and Real (1986) used mean values of R_n and Δ and statistical values of the slope and intercept of the lower limit from the data of Idso (1982) to calculate values of r_a. They reported values ranging from 4.0 to 12.5 s m^{-1} for corn, tomato, sugarbeet, guayule, and potato. Windspeed values were not given. Using Eq. (9) with their estimated average values of R_n, calculated r_a values ranged from 5 to 13 s m^{-1} for windspeeds ranging from 5 to 1 m s^{-1}. Although the agreement between these values is encouraging, direct observation of all parameters, and a more rigorous definition of r_a, will be needed before validation of Eqs. (5) and (6) can be considered complete.

Conclusions

The temperature of a plant canopy is determined by the water status of the canopy and by environmental factors such as net radiation, vapor pressure deficit, and windspeed. Using canopy temperatures as an index of the water status of a crop is not feasible unless the temperatures can be normalized for environmental variability, leaving only the water status as the determining factor. The empirical approach utilizes experimentally determined, fixed upper and lower temperature limits to normalize the temperatures. The theoretical approach, for full cover canopies, allows the upper and lower limits to be determined by environmental conditions at the time of measurement, with only two parameters, the canopy resistance at potential evapotranspiration and the crop height, to be determined by experiment.

The semi-empirical equation proposed by Thom and Oliver (1977) appears to yield, somewhat unexpectedly, adequate values of the aerodynamic resistance for *both* stable and unstable conditions. Introduction of interception coefficients, 0.9 for the lower limit to account for soil heat flux, and 0.8 for the upper limit to account for the soil heat flux and an increase in reflected and emitted radiation when the canopy is considered instantly desiccated, effectively reduce the net radiation. When these factors are used in Eqs. (5) and (6), and aerodynamic resistance calculated using Eq. (9), predicted values of the upper limit compared well with the few data reported in the literature.

The requirement that R_n and U be known adds a complication to the measurement of the CWSI as an operational technique. Ideally, measurements of R_n and U should be made concurrently with the temperature and vapor pressure measurements. Operationally this could be difficult to implement. However, it may be possible to derive tabular values for different times of day and days of year from which R_n could be estimated, at least for clear sky conditions. The term r_{ae} does not change drastically with windspeed (Eq. 9), so it may be possible to estimate this factor qualitatively as low, medium and high.

The evaluation of canopy resistance at potential transpiration should be no more difficult than the determination of non-water-stressed baselines for the empirical approach. By accounting for intercepted net radiation and windspeed, the theoretical approach for calculating the CWSI holds promise for improving the evaluation of plant water stress. Further experiments should refine the calculation of r_{ae} and the estimation of I_c and r_{cp}, and make this method operationally viable.

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